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Open Architecture, Inventory Pooling and Spare Maintenance Assets

18 October 2007

by

Dr. Geraldo Ferrer, Associate Professor

Graduate School of Business & Public Policy

Naval Postgraduate School

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Abstract

The adoption of open architecture affects several economic components in the life of an asset, including developmental costs, maintenance costs, and inventory management costs. This article focuses on the benefits provided by pooling together the inventory necessary to meet the demand of many users into a small number of storage sites with reduced product variety obtained with the adoption of Open Architecture (OA). The example showcased in this analysis, distribution of spare engines for the F-16 in continental United States, supports open architecture as the right design approach to reduce expenditures in the acquisition of valuable assets without compromising availability.

Keywords: open architecture, inventory management, pooling effects, product reuse

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Introduction

The combined use of commonality and modularity in product design has allowed automobiles, aircraft, computers and a host of other durable assets (including most military systems) to be reusable beyond their first lifecycle and to be given many more lives. This versatility substantially impacts the availability and maintenance cost of many durable assets. Modularity enables the division of the product development effort among many specialists (firms or individuals). Therefore, the development of the most advanced and competitive systems is ensured. Modularity also facilitates the separation of component-wear phenomena as the system ages, enabling the maintenance professional to localize and repair damaged modules without affecting the durability of other modules in the system.

Commonality also facilitates the development of new systems using modules that were previously designed and developed for an existing system, providing major time and cost savings to the organization that can exploit these benefits. In other words, thanks to commonality, high-value modules in a system may be recovered at the end of the system's life and used in another product—a process often called cannibalization.

Commonality, however, presents a disadvantage that many purchasing professionals will recognize: the adoption of common design in a competitive environment hinders creativity and innovation in product development. Suppliers of high-technology products would prefer to develop their own designs than to share them with competitors. The design team would rather showcase its capability in product design, especially in the development of expensive items or in the adoption of new technologies. Hence, while modularity remains a powerful product-development philosophy that brings agility and cost reduction to product design, the adoption of common designs for complex modules may be not the best approach to system acquisition—especially in circumstances requiring the development of advanced technologies. In these scenarios, the traditional "commonality" must be

enhanced with the adoption of "open architecture" features—allowing modules from competing sources to be used in the same system, without constraining the creativity and innovation from the designers involved in the development of the module. The Defense Acquisition University (2006) defines Open Architecture as:

> The confluence of business and technical practices yielding modular, interoperable systems that adhere to open standards with published interfaces. This approach significantly increases opportunities for innovation and competition, enables reuse of components, facilitates rapid technology insertion, and reduces maintenance constraints.

Modularity and commonality are the two aspects in product design that support the adoption of an open architecture. They facilitate the execution of an agile product development program with a wide-reaching product line that meets the requirements of multiple users with different needs. The renewed emphasis on open architecture allows strategic resource allocation, facilitating the acquisition of better assets with lower costs.

A current example of this design approach is the F-35 Lightning II, Joint Strike Fighter, a multi-role strike fighter aircraft currently in production for the uniformed services of the US Department of Defense and for many of the US allies. The Federation of American Scientists describes the following among its strengths (2005a), "JSF will benefit from many of the same technologies developed for F-22 and will capitalize on commonality and modularity to maximize affordability."

In practice, previous development and acquisition of weapons systems by the DoD usually did not have this focus. For instance, Pratt & Whitney (P&W) and General Electric Aircraft Engines (GEAE) produce engines for the F-16 aircraft used by the US Air Force and a few foreign military forces. The P&W F100-PW-200 aircraft engine was originally selected over GEAE's offering as the sole source engine for the F-16. The original F-16 was designed as a lightweight, air-to-air day-fighter. Air-to-ground responsibilities transformed the first production F-16s into multi-role fighters. The first operational F-16A was delivered in January 1979 to the 388th Tactical Fighter Wing at Hill Air Force Base, Utah. The delivery of 2,200+

aircraft to the US Air Force continued until March 2001 (Federation of American Scientists, 2005b).

The decision to choose an alternate fighter engine for the F-16 led to the development of the General Electric Aviation Engine's F110 series. With the implementation of the Alternative Fighter Engine (AFE) competition for the F-16 in 1985, GEAE fielded the F110-GE-100 version to compete with Pratt & Whitney's F100-PW-220 engine. Throughout the production of the F-16, the performance requirements for both suppliers were identical, but the engines delivered were not interchangeable. In fact, the airframe manufacturer, Lockheed-Martin, had to deliver structurally different frames to use the different engines. For example, aircraft with production numbers ending in zero are designed and built with significantly larger air intake to accept the GEAE F110 series engine. Aircraft with production numbers ending in two are designed and built with smaller air intake to use the P&W F100 series engine. Each engine type (GEAE or P&W) used different control software (with implications in the cockpit controls and pilot training), requiring a unique airframe interface. With the exception of the engine, the airframe interface and the control software, aircraft of the same generation would otherwise be identical.

The adoption of two engine suppliers for the F-16 fighter aircraft was intended to eliminate the monopoly held by Pratt & Whitney as the sole-source engine supplier for that aircraft. However, allowing the newcomer (GEAE) to design a product that was not interchangeable with the existing engine did not eliminate some of the monopoly effects in the long-term, and created costly logistics constraints.

Similar to the F-16 acquisition experience in the '80s and '90s, the Joint Strike Fighter acquisition process includes the development of two competing power plants: the Pratt & Whitney F135, and the GEAE F136, developed in partnership with Rolls-Royce. In its website, the Federation of American Scientists states that the F-35 propulsion systems will be "physically and functionally interchangeable in both the aircraft and support systems." According to the Joint Strike Fighter Program

Office, “the F135 and F136 teams are working closely to develop common propulsion system components” (F-35 JSF Program, 2007).

Open architecture provides the opportunity to introduce product aggregation—one of the three aggregation (or *pooling*) approaches to managing and improving supply-chain performance, along with time aggregation and place aggregation. Product aggregation is intended to reduce product variety without compromising the functionality required by the user.

In this study, I use current inventory data of P&W and GEAE spare engines (held in various bases in the continental United States to support the F-16 operations) to identify substantial cost reduction with the pooling effects that could be achieved with the adoption of better inventory allocation (place aggregation), as well as the use of open architecture (product aggregation) at the time these engines were developed. One important caveat exists, however: considering the limited amount of usable data available about the acquisition and use of these aircraft, the reader is cautioned that this analysis is not a critique of the acquisition of the F-16 aircraft or its engines.

Instead, the purpose of this research is to propose an approach to adopting open architecture as the guiding philosophy in the design and acquisition of complex systems with advanced technologies. Moreover, this study provides a useful estimate of the cost benefits that similar programs might enjoy if product and place aggregation are jointly used to pool inventory. It is an assumption of this study that a complex system (such as the Joint Strike Fighter, or other weapon systems in use by the uniformed services of the Department of Defense) is a combination of hardware and software components that may be acquired from multiple developer/suppliers. This study shows that the adoption of open architecture in the acquisition of these systems can substantially reduce the cost of these programs.

Open Architecture of Complex Systems

Engine maintenance technicians remove engines from aircraft for three principal reasons:

1. To perform scheduled or preventive maintenance (scheduled engine removal, or SER);
2. To perform unscheduled maintenance requirements due to engine failure (unscheduled engine removal, or UER); and
3. To facilitate other maintenance (FOM), meaning the engine is fully operable, but must be removed from the aircraft to provide access to other components requiring maintenance within the aircraft.

Each base has specific engine maintenance capabilities. In some cases, an engine or engine components (modules) may be removed and transported to Tinker AFB (OK), the maintenance depot for F-16 engines, without any maintenance action by local technicians. In other cases, local technicians may be capable of performing the required maintenance action internally and returning the engine to serviceable or Ready for Issue (RFI) status.

The managers of active duty air force bases aggressively track the status of engine changes. They expect turnaround of less than 24 hours from each engine change operation, which requires keeping a certain inventory of spare engines in each base. This culture seems to contrast with Air National Guard (ANG) and Air Force Reserve (AFR) units, in which the F-16 aircraft are used less intensively. Guard and Reserve units typically have fewer assigned aircraft and, therefore, have a lower spare engine stock. However, given that their primary mission is the defense of the national air space, they too would benefit from keeping a brief engine maintenance turnaround.

Open Architecture as an Agent to Simplify the Supply Chain

The US Air Force uses the F-16 in 30 bases of various sizes, including Active Duty (AD), Air Force Reserve (AFR) and Air National Guard (ANG). Each base has its own stock of spare engines to meet its own demands. Moreover, some of the bases use aircraft with GE engines; others use aircraft with P&W engines. As explained earlier, bases do not use engines of different make in their fleets because they are not interchangeable in any way. The most notable differences associated with the two power plants are:

1. Airframes are structurally different, with a distinct engine bay for each engine make.
2. Engines have different durability and reliability, leading to distinct preventive maintenance needs.
3. Repair parts, maintenance jigs and tools are different.
4. The software that controls engine performance and interprets the pilot's command from the cockpit is different.
5. Aircraft using different engines respond differently to the pilots' commands. This mandates a non-trivial period of adaptation when a pilot switches from one aircraft type to the other.

In short, because of different design choices made by the engine manufacturers, we have effectively two distinct aircraft types in service under the codename F-16. This creates undesirable limitations in the way aircraft and engines are used and maintained.

The open architecture design approach would effectively eliminate many of the differences between the two engines, without constraining the creativity and flexibility of the design engineer. The concept stems from the development approach used by many software houses, in which sub-routines (modules) are developed by individual designers having only two major constraints: the functionality (i.e., the sub-routine does what is expected to do) and the standardized interface with the main program.

Nelson (2007) indicates that open architecture principles have been around since at least 1981, when IBM developed its personal computer. The design of the IBM-PC was a major breakthrough in that it was made of a set of physical modules that could be replaced by similar modules of different design, make or performance, as long as they satisfied a limited set of interface requirements and fulfilled the expected functions. For example, a hard disk drive of a given capacity and make could be upgraded by another hard disk of different make and greater capacity, as long as it satisfied a simple set of interface constraints. By contrast, one isn't usually able to replace the engine of an automobile by one from a different maker, even if the two have similar performance, size or functionality.

The open architecture design philosophy was extremely successful for desktop computers, and it still describes over 90% of all desktop computers used 26 years later. In contrast, proprietary designs have lead to expensive and less successful products in the computer industry—such as the computer Amiga that preceded the IBM-PC, the short-lived Unix desktop, and even the various generations of the Macintosh desktop.

With the exception of the IBM-PC, the adoption of open architecture in computer hardware design is limited. Space and weight limitations have restricted the use of open architecture in the design of laptop computers. Hence, internal components developed for one particular laptop usually cannot be used in a different model or brand. Open architecture benefits have been usually restricted to the interfaces with external accessories and, in some cases, to memory units.

It is important not to confuse open architecture with "open source" (Coar, 2006). Software developed under an open source philosophy is copyright-free and can be modified and extended by any other software writer, as exemplified by the Linux operating system and the Mozilla web browser. Nonetheless, to enable continued expansion, open source software usually adopts open architecture as the means to ensure a compatible interface between the works of multiple authors.

In 2006, the US Navy released the *Open Architecture Contract Notebook,* explicating the open architecture guidelines to be adopted by Acquisition Officers (PEO-IWS, 2006). Specifically, it is recommended that contracts include this statement: "The Contractor will be required to define, document, and follow an open systems approach for using modular design, standards-based interfaces, and widely supported consensus-based standards" (p. 7).

While these recommendations usually target software design, they can be quite useful in the design and acquisition of all complex hardware, including weapons systems. The adoption of open architecture principles in hardware design provide some of the same benefits found in software design, in addition to:

1. Simplified maintenance: the modularity found in open architecture products makes it easier to remove, replace and repair damaged modules with minimal impact to the whole system.
2. Simplified logistics: open architecture enables the use of modules by different makes, or even different generations, if they maintain the same interface standards.
3. Reduced acquisition cost: open architecture allows a true competition between potential suppliers in all phases of the lifecycle of the product, requiring just that each potential supplier adopt the standard module interfaces.

These benefits become more critical when we realize that all weapons systems depend on the successful integration of multiple hardware and software modules. The determination of standard interfaces between modules allows substantial savings in the operation and maintenance of weapons systems, as illustrated by the F-16 aircraft engine.

Inventory Allocation of Spare Engines for the F-16

This section describes the inventory management of the F-16 spare engines, as practiced by the Air Force bases that use this aircraft. The annual demand for spare engines in these bases was 656 P&W engines and 752 GEAE engines in 2007, reflecting a negative trend of approximately 5.8% per year since fiscal year 2000. Demand originates in 13 bases using Pratt & Whitney-powered aircraft, and 18 bases using General Electric-powered aircraft in the Continental United States. In general, these bases hold a total pre-positioned inventory of 159 spare engines, turning the inventory fewer than 9 times per year. Table 8 in the Appendix shows the historic demand in each base, in addition to the International Civil Aviation Organization (ICAO) code of the respective airfield. Based on a simple linear regression of the 8-year demand in each of the 31 bases, the forecast demand for year 2008 is also shown in the table. As we can observe, approximately half of the forecasted demand is fragmented across 24 Air National Guard (ANG) bases, and the remainder is distributed in four Active Duty (AD) bases; a small demand is generated in two Air Force Reserve (AFR) bases. Notice that four ANG bases are co-located with AD bases (Andrews AFB (DC), Kelly AFB (NM), Buckley AFB (CO) and Kirtland AFB (NM)), where valuable synergies regarding engine maintenance may be expected. Each base has different capabilities to provide maintenance to the engines, with all the complexity that such maintenance entails. In general, the ADs have the support personnel and equipment to give some service, while the ANGs and AFRs have limited maintenance infrastructure.

To prevent shortage of engines, which would affect the readiness of the respective base, a base-stock inventory management policy is adopted such that a prescribed level of inventory is kept at each based. The Oklahoma City Air Logistics Center, located at Tinker AFB, provides “supply chain management, including acquisition, repair, storage, distribution, disposal and the technical and engineering services for the center’s assigned engines,” which include major maintenance

activities for the F100 and F110 engines (Tinker AFB, 2007). This depot is conveniently located in the center of the country, but only seven bases are within one-day driving distance (approximately 550 miles)—an important consideration since managers expect to maintain the base stock level at all times. Traveling time to other bases is as long as 3 days. Hence, the lead time for an order placed from each base is typically between 5 and 7 business days, depending on the distance to the customer and provided that Tinker has the engine in stock ready for issue.

INVENTORY STATUS: Each base stores its own replacement engines.			
	P&W	GEAE	Total
Annual Demand	656	773	1429
Base Stock	38	48	86
Safety Stock	18	22	40
Safety Stock Value	$58.9	$65.0	$123.9

Table 1: Inventory Distribution According to Category and Make

The US Air Force propulsion requirements determine the spare engine inventory level, adding a safety stock based on the demand variability and on the service level associated with the user's priority. This service level depends on the primary assignment for each location: either combat (80% service level), or training (70% service level). All F-16 users in this study are considered combat units—except those located at Luke AFB (AZ), which is a training base (Henderson & Higer, 2007). The demand variability is caused by two random variables that regulate the queuing system at the Tinker AFB maintenance depot:

1. Number of hours flown per month: this variable drives the actual demand seen at the depot.

2. Maintenance service time: this variable drives the waiting time until an engine can be serviced at the depot.

The asset utilization randomness drives the need for a safety stock. Considering the forecasted demand for 2008, and the unit prices of $3.27M (P&W) and $2.95M (GEAE), the recommended safety stock in all bases is worth $123.9M, as shown in Table 1. This base stock policy meets the forecasted demand according to the current practice of each base keeping its own inventory. The difference between the base stock and the safety stock (86 – 40 = 46) is the sum of the expected lead-time demand in each site.

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Two Approaches to Spare Engines Storage

In what follows, we look at some alternative approaches to spare engine storage that meet an 85% service level in all bases at a lower cost than what is currently practiced by the Air Force.

Centralized Storage

It is a well-known statistical fact that when two variables with independent randomness are merged, the resulting variable is proportionally less variable. For example, if base A has monthly expected demand of 8 spare engines with standard deviation of 3, and base B has monthly expected demand of 10 spare engines with standard deviation of 4, their joint monthly expected demand is going to be 18 (= 8 + 10) with standard deviation of 5 ($= \sqrt{3^2 + 4^2}$), *provided that the demand uncertainty in one base is not correlated with the uncertainty in the other base*. The coefficient of variability of the resulting variable, the ratio between the standard deviation and the mean, drops from $cv_A = 0.375$ and $cv_B = 0.4$ respectively to less than 0.28 (= 5/18), indicating that the joint demand faces lower variability than each of the two demands do separately. Moreover, recent demand data (Table 8) suggests that there is no correlation between the changes in demand in each base. Hence, to manage the demand variability of two or more bases, it is necessary to hold lower aggregate inventory in a single facility than it is to hold each inventory separately.

This simple example has powerful applications that are often ignored. For instance, Tinker AFB (OK) does not have any assigned F-16 aircraft. However, considering its status as the maintenance depot and its central location, it is conceivable to store all F-16 engines at the depot, regardless of make, and ship them directly to the respective base when needed. Pooling this demand under a single inventory would reduce the safety stock, generating substantial savings. Under this policy, the total inventory of Pratt & Whitney engines necessary to satisfy

demand (with the same degree of confidence in satisfying the demand in each base) would drop from 38 (see Table 1) engines to 18 engines, as shown in Table 2. Likewise, GEAE engine inventory would drop from 48 to 20. These inventory reductions would be credited exclusively to the reduction in the safety stock; in other words, to achieve the same service level, a centralized (or *pooled*) inventory requires a smaller safety stock than a distributed (or *pre-positioned*) inventory.

INVENTORY STATUS: All replacement engines stored at Tinker AFB			
	P&W	GEAE	Total
Annual Demand	656	773	1429
Base Stock	18	20	38
Safety Stock	5	5	10
$ Safety Stock	$16.4	$14.8	$31.1

INVENTORY STATUS: All replacement engines stored at Tinker AFB. OA allows using engines of different makes in any F-16 airframe.	
	All Makes, Common Interface
Annual Demand	1429
Base Stock	35
Safety Stock	7
$ Safety Stock	$21.71

Table 2: Central Storage of Spare Engines at Tinker AFB

In addition to adopting a centralized inventory, if the engines were designed using an open architecture, we would be able to reduce the inventory further, from 38 to 35 engines. The safety stock would reduce by 30%, from 10 to 7 units. OA would require that P&W and GEAE engines could be used interchangeably in any airframe.

There may be a few weaknesses associated with this initial solution. Considering that the standard procedure is to ship F-16 engines using exclusively air-ride-equipped tractor-trailers, it is necessary to ensure that the drive time to receive the engine when ordered from the field is less than one day. Hence, inventory consolidation at only one central location might not meet the operational needs: it would impose up to a three-day traveling time between the inventory and some users, compromising their readiness. However, according to users in the field, one business day (550 miles driving distance or less) is an acceptable traveling time for a replacement engine.

Proponents of pre-positioning will point to availability (or *readiness*) as one of its greatest benefits. However, just as the centralization of the inventory in a single location is inefficient, pre-positioning is costly and may expose the user to potentially lower inventory availability (due to increased demand variability) unless there is an additional investment in safety stock. In what follows, we look into an alternative approach that does not centralize the inventory in a single location. Rather, it combines some of the advantages of pre-positioned inventories with that of an aggregate storage plan.

Regional Storage

First, we consider regional storage without the adoption of an open architecture design. Then, we examine the benefits of open architecture in designing the distribution network of regionally distributed inventory.

There is one caveat to acknowledge: a transportation model using integer program would not be a useful approach to find the storage points in this problem for two main reasons: (1) The problem is fairly complex to be analyzed using software typically available to most managers (MS Excel and Solver). (2) Most important, if every customer is also a potential sourcing point, and the number of storage points is pre-determined but not pre-identified, the solution process would encounter

discontinuities in the objective function. This would prevent us from finding the optimal solution, even for a small problem with just 13 customers.

Hence, to identify the bases that are the best candidates for holding the distributed inventory, we use a modified version of the heuristic proposed by Ardalan (1988). The heuristic requires the development of a table of distances between potential inventory locations and users, as well as the assignment of weights to help prioritize the decisions. It is a greedy procedure that sequentially identifies the locations that are closest to the most demanding users until all warehouses are identified.

In this problem, the table of distances was created with *Yahoo! Maps* (http://maps.yahoo.com). Each column represents a candidate storage point, and each row represents a customer. In each cell, the value (x_{ij}) is the distance from base *j* to base *i*. As recommended by the heuristic, an Ardalan table is created as the product between the user's demand (d_i), the table of distances (x_{ij}), and a weight associated with that delivery (w_j). Because of existing resources at active duty bases, it is usually more desirable to store engines at AD bases than at ANG or AFR. Moreover, it is more desirable to store engines at Tinker AFB than at any other AD base because it is the depot that provides major maintenance support for the F-16 engines. Hence, this modified Ardalan matrix assigns weights to the sources (w_j) that act as a "source penalty," rather than to customers, which would indicate their priority levels. Since Tinker is the ideal source, its weight is 1. Other AD bases received a weight of 1.1, while the AFR and ANG sites received a weight of 1.5. Summarizing, to create a distribution network for *k* customers, this process generates a square matrix with *k* rows and columns in which the value of each cell (a_{ij}) is determined by the expression:

$$a_{ij} = d_i x_{ij} w_j$$

Comparing the resulting cells, a high number indicates an onerous delivery (high demand * long distance * high penalty). A low result indicates a relatively

inexpensive delivery (low demand * short distance * low penalty). This matrix, largely based on the Ardalan heuristic, is the root of the procedure to identify a set of storage locations that require low transportation time to the respective users and provide the benefit of inventory aggregation. The following steps identify the optimal storage locations:

Step 1: Let $s = 1$. This variable is the number of storage points at the end of this round.

Step 2: Generate the array $A_j = \sum_i a_{ij}$, a proxy for the weighted sum of all shipments from storage point j to each customer i.

Step 3: Identify $A_m = Min\{A_1, \ldots, A_{k-s+1}\}$. Column m defines the least onerous storage location in round s.

Step 4: Move column m to the end of the matrix.

Step 5: For each cell (i, j) that satisfies $j \le k - s$, let $a_{ij} = Min\{a_{ij}, a_{mj}\}$.

Step 6: If a stopping point is reached, stop. Otherwise, let $s = s + 1$ and repeat steps 2 through 5.

The stopping point could be, for instance, a pre-established number of storage facilities or some capacity limitation. In this case, we added storage points until all users were served by inventories within a one-day drive (approximately a 550-mile distance). However, as any heuristic, some exception may be necessary to ensure that it finds a solution that is efficient (low cost) and effective (meets all practical constraints). Consequently, each low-cost location indicated by the heuristic should be selected as a new storage point only if it increases the network coverage, i.e., one or both conditions are satisfied: (1) the low-cost location is not within one-day drive from any of the existing storage locations, and (2) the low-cost location is within one-day drive from a customer that cannot be served by any of the existing storage locations. If these conditions are not satisfied, that low-cost location is not contributing with the inventory-pooling objective, and the next low-cost location is selected in its place.

The heuristic is illustrated with the allocation of the Pratt-Whitney spare engines, in Table 3. All 13 customers are served from 6 storage locations, shown in Figure 1. Nellis AFB NV (LSV), located within a one-day drive distance from two previously assigned storage locations (LUF and HIF), does not improve network coverage, so it is not selected in rounds 5 and 6. The next lower-cost location in each round, DLH (ANG-Duluth MN) and FWA (ANG-Ft Wayne IN) are selected instead. Notice that despite the inventory pooling efforts, three locations (Hill AFB-Depot UT, ANG-Duluth MN and ANG-Burlington VT) store inventory for just their needs, because of their distance to other bases using the same type of engine.

Once the low cost storage locations are identified, each user *i* is assigned to the storage location *j* that satisfies the equation $a_{ij} = Min\{a_{i,k-s+1},\ldots,a_{i,k}\}$. Each storage location holds the inventory to meet the demand for all users assigned to it, in addition to a safety stock. This safety stock is based on the demand variability in each base supplied by that location, and by the lead-time for that location to resupply from the central depot in Tinker. Locations holding inventory for multiple users benefit from the pooling effect already discussed.

Heuristic round	Lowest cost location	Selected distribution points	Users within range
s = 1	LUF	LUF	4
s = 2	TIK	LUF, TIK	8
s = 3	BTV	LUF, TIK, BTV	9
s = 4	HIF	LUF, TIK, BTV, HIF	10
s = 5	LSV (DLH)	LUF, TIK, BTV, HIF, DLH	11
s = 6	LSV (FWA)	LUF, TIK, BTV, HIF, DLH, FWA	13 (all)

Table 3: Heuristic application to the Pratt-Whitney spare engines allocation problem.

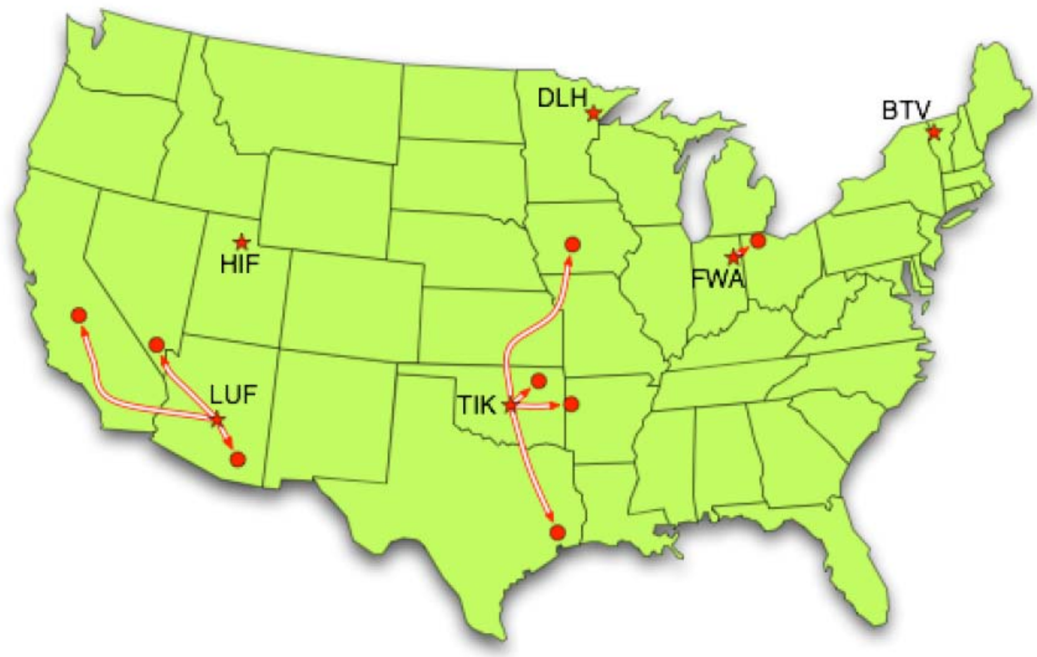

Figure 1. Regional Storage of Pratt & Whitney Spare Engines[1]

For example, Luke AFB (LUF) holds inventory for its own needs and for three other bases (ANG-Tucson AZ, Nellis AFB NV, ANG-Fresno CA). The standard error of the forecasted annual demand (260 business days) from each of these bases range between 10.3 and 19.1. However, the standard error of the aggregate demand is just 31.4. Considering a lead-time of 6 business days from TIK (the depot) to LUF, the safety stock to meet the demand variability of all four bases is just 4.9 units. Also, the aggregate expected demand from the four users is 440 units per year (or 10.2 units during the lead-time), which leads to a base stock of 16 units. Detailed information about the inventory allocations appears in Table 9 in the Appendix, including the distance from each base to the respective storage locations.

Using the heuristic to assign storage points for GEAE spare engines, eight storage locations are sequentially identified (as shown in Table 4). In this case, no

[1] All maps: Storage locations identified as a star. Users identified as a circle. Typical roads are shown.

exceptions are necessary, since every allocation suggested by the heuristic increases the network coverage—adding at least one base to within the one-day delivery threshold. In this analysis, eight bases are needed to hold the inventory for 19 bases using GEAE engines, as shown in Figure 2. Once again, two bases (AFR-Homestead FL and ANG-Montgomery AL) hold inventory exclusively for their needs because of their distance to other bases using the same engine. Table 10 in the Appendix shows the regional storage points, the size of the respective inventories, and the distance from each base to the respective inventories.

Heuristic round	Lowest cost location	Selected distribution points	Users within range
s = 1	TIK	TIK	4
s = 2	HIF	TIK, HIF	6
s = 3	ADW	TIK, HIF, ADW	12
s = 4	SGH	TIK, HIF, ADW, SGH	14
s = 5	HST	TIK, HIF, ADW, SGH, HST	15
s = 6	MGM	TIK, HIF, ADW, SGH, HST, MGM	16
s = 7	CVS	TIK, HIF, ADW, SGH, HST, MGM, CVS	17
s = 8	FSD	TIK, HIF, ADW, SGH, HST, MGM, CVS, FSD	19 (all)

Table 4: Heuristic application to the GEAE spare engines allocation problem.

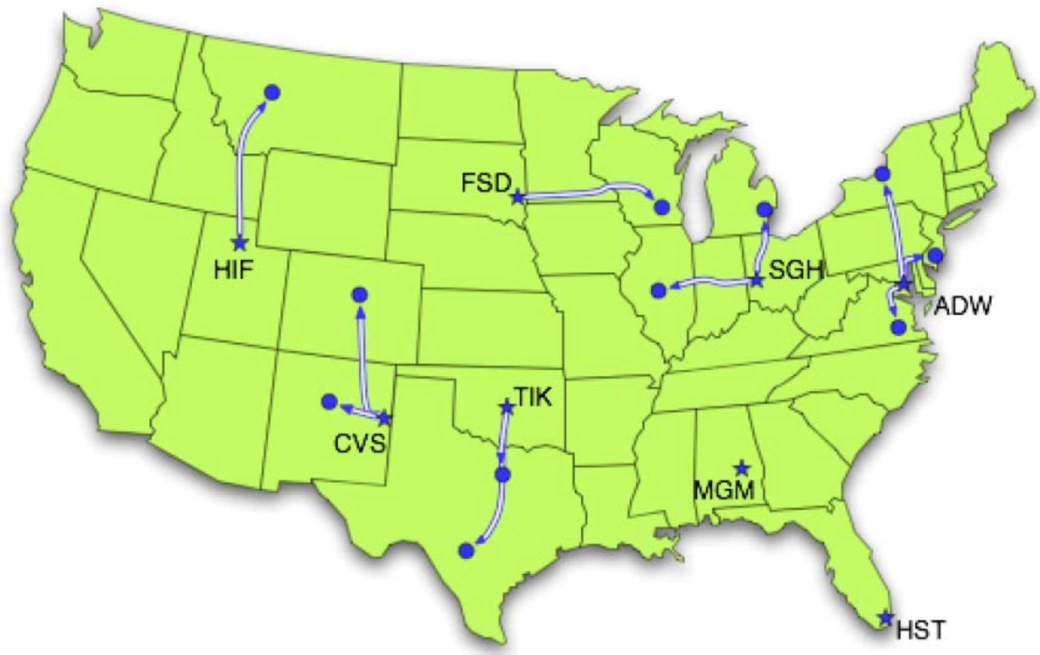

Figure 2. Regional Storage of General Electric Spare Engines

As the analysis shows, regional storage reduces the size of safety stock of P&W engines from 18 to 11 engines and the safety stock of GEAE engines from 22 to 15 engines, in contrast to the fully distributed storage of engines shown in Table 1. By pooling the variable demand from each base into a limited number of storage points, the coefficient of variation of the forecasted demand is reduced, which leads to lower safety stock requirement and substantial savings. This inventory allocation requires that two users (ANG-Des Moines IA and ANG-Gt Falls MT) be served by inventory located more than 500 miles away, but no more than 600 miles from the user. Yet, it is expected that this allocation allow all bases to receive their spare engines within one day of the request.

Regional Storage with Open Architecture Benefit

The regional storage performance could be substantially improved if the engines were designed with an open architecture mindset. Without OA, the

inventory distribution in Figure 1 and Figure 2 benefits only from the risk-pooling effect observed when we aggregate the demand variability of several customers with a common safety stock. In addition to benefits associated with simpler design and maintenance of these complex assets, the adoption of open architecture would increase the number of bases in some geographic regions that could be served by the same storage location, adding another dimension of supply-chain aggregation to reduce the need for safety stock. This pooling effect created by open architecture is called *product aggregation*: different products that are perfect substitutes can be held as a single inventory pool; this aggregation has the same risk-pooling effect as observed when we pool inventories from different locations.

Heuristic round	Lowest cost location	Selected distribution points	Users within range
s = 1	ABQ	ABQ	6
s = 2	ADW	ABQ, ADW	15
s = 3	HIF	ABQ, ADW, HIF	18
s = 4	LUF	ABQ, ADW, HIF, LUF	19
s = 5	TIK	ABQ, ADW, HIF, LUF, TIK	24
s = 6	FWA	ABQ, ADW, HIF, LUF, TIK, FWA	26
s = 7	FSD	ABQ, ADW, HIF, LUF, TIK, FWA, FSD	28
s = 8	HST	ABQ, ADW, HIF, LUF, TIK, FWA, FSD, HST	29
s = 9	MGM	ABQ, ADW, HIF, LUF, TIK, FWA, FSD, HST, MGM	30 (all)

Table 5: Heuristic application to the complete spare engines allocation problem.

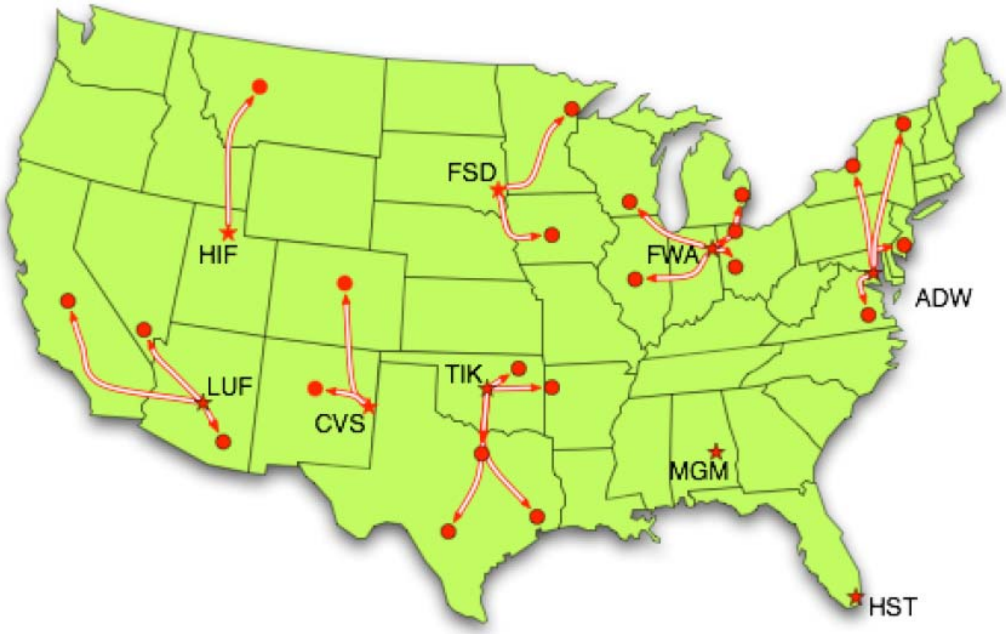

Figure 3. Regional Storage of Spare Engines with OA Benefit

The same heuristic used earlier to find separate inventory storage can be used to find storage locations for spare engines built using open architecture. The separate inventory allocation required 6 bases for storage of P&W engines and 8 bases for storage of GEAE engines. The joint allocation proceeds as shown in Table 5. In this environment, engines from either manufacturer could be used in any airframe. To meet the demand of all 30 bases from locations within a one-day drive, nine storage points suffice, shown in Figure 3. Among the selected storage points, there are three Active Duty bases, one Air Force Reserve and five Air National Guard sites. Notice that among the ANG bases, there are two that are co-located with AD bases (ANG-Albuquerque NM and ANG-Andrews DC). These may enjoy some support from this arrangement. Detailed information about the inventory allocation is in Table 11 in the appendix.

Open architecture increases the population density of users that can be served from the same overall inventory pool. In the original allocation, there were 12 bases storing spare engines (two of them storing both types), which amounted to 14

different inventory pools. With this approach, only nine storage points are necessary. Notice that only two bases (ANG-Montgomery AL and AFR-Homestead FL) remain isolated, holding just the engines required to provide for their own needs. This is quite an improvement from the previous solution without OA, in which five locations were isolated. Table 6 summarizes the performance of regionalized storage with and without the benefit of open architecture. Thanks to this added level of aggregation, the total safety stock necessary to absorb the variability of demand seen in 30 bases is now just 21 units, contrasting quite favorably with the safety stock of 40 engines in the distributed mode adopted today (see Table 1).

INVENTORY STATUS: Replacement engines stored at a limited number of bases.			
	P&W	GEAE	Total
Number of Storage Bases	6	8	12
Annual Demand	657	772	1429
Base Stock	29	37	66
Safety Stock	11	15	26
Safety Stock Value	$36.0M	$44.3M	$80.3M

INVENTORY STATUS: Replacement engines stored at a limited number of bases. OA allows using engines of different makes in any F-16 airframe.	
	All Makes, Common Interface
Number of Storage Bases	9
Annual Demand	1429
Base Stock	59
Safety Stock	21
Safety Stock Value	$65.1M

Table 6: Regional Storage of Spare Engines

As Figure 3 shows, the use of open architecture greatly improves the distribution network in the Northeast, Southwest, the Midwest and in the central part

of the country, where four storage locations (Tinker AFB, Luke AFB, Andrews AFB and Fort Wayne) serve 20 bases. On the downside, three bases are served by inventory located between 500 and 580 miles away, stressing the operational constraint in this distribution process. However, most users sit within a one-day drive from one or more additional storage points. Consequently, the safety stock necessary to manage the demand variability of all 30 bases, which used to be 40 units in the original allocation (see Table 1), is now just 21 units. Considering that the average engine costs the DoD approximately $3.1M, this reduction accounts as direct savings of $58.8M—a savings due to the adoption of open architecture in a regionalized inventory distribution.

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Discussion and Future Research

An important concern in supply-chain management is the identification of aggregation opportunities that exist in the design, storage and distribution of goods to the final customer. This aggregation, or *pooling*, can take place in three dimensions: time aggregation, place aggregation and product aggregation. The manager should evaluate the trade-offs in each of these aggregation opportunities in order to implement the correct product design, storage and distribution procedures. Time aggregation implies that the inventory is kept to meet the demand over longer or shorter periods of time. Place aggregation implies that the inventory is designed to meet the demand over one or many markets. Finally, product aggregation implies that a product or component is designed to meet the demand associated with one or more applications or customer needs. When any or all of these aggregations are viable, the company enjoys substantial operational savings due to the reduction of safety stock; in addition, much of the coordination effort may be reduced. This paper deals with the last two types of aggregations: place and product. Here, product aggregation is achieved with the adoption of open architecture in product design.

The purpose of this study is to evaluate the economic impact of adopting open architecture in the design of complex assets to reduce the lifecycle cost of maintaining those assets. The adoption of open architecture affects several economic components in the life of the asset, including developmental costs, maintenance costs, and inventory-management costs. Of these three components, this article focuses on the inventory-management costs—in particular, on the benefits of pooling the inventory necessary to meet the demand of many users into a small number of storage sites with reduced product variety.

The current distribution of spare engines for F-16s was used to illustrate and evaluate the benefits of place and product aggregation. Starting from a status quo position, in which the inventory is locally distributed in the hands of each AD, ANG and AFR user, and considering that there are two engine makes (Pratt & Whitney

and General Electric) that are not interchangeable because of their unique designs, I evaluated four alternative distribution models representing different aggregation approaches: with or without open architecture (product aggregation) and centralized or regionalized distribution (place aggregation). As expected, both types of aggregations provided inventory reduction. What perhaps was not expected was the dimension of the safety stock reduction, shown in Table 7.

One important concern is the impact of regional storage on transportation costs. To facilitate comparison, the analysis included a measure of expected miles driven to each facility, considering that each engine would generally be transported from the depot at Tinker to a regional storage base, and then from the regional storage base to the user. The baseline measure of 1.41 million miles is the product between the number of units shipped from Tinker and the distance to each user, shown in Table 7. This total is the same, whether the storage is centralized at Tinker or distributed among all users. Pooling the storage into 12 bases (without open architecture) would increase the distance driven—and the transportation cost—to just 1.51 million miles. If the storage is pooled into just 9 bases (with open architecture), the distance driven is increased to 1.55 million miles—10% more than the baseline, a small increase, considering the safety stock reduction of 47%.

		Product Aggregation	
		Open Architecture	Proprietary Design
Place Aggregation	central	storage points: 1 safety stock: 7 safety stock value: $21.7M demand-miles: 1,412k	storage points: 1 safety stock: 10 safety stock value: $31.1M demand-miles: 1,412k
	regional	storage points: 9 safety stock: 21 safety stock value: $65.1M demand-miles: 1.554k	storage points: 12 safety stock: 26 safety stock value: $80.3M demand-miles: 1,512k
	local	storage points: 30 safety stock: 38 safety stock value: $117.2M demand-miles: 1,412k	storage points: 30 safety stock: 40 safety stock value: $123.9M demand-miles: 1,412k

Table 7: Performance of Different Aggregation Approaches

Important Lessons Drawn from this Study

1. Open architecture is an effective means of product aggregation to facilitate supply-chain improvement for valuable complex assets.

2. Open architecture can be leveraged by place aggregation when the asset is used by several facilities geographically distributed.

3. Open architecture provides the greatest inventory reduction benefit when storage can be centralized. However, it can still provide substantial benefits when centralization is not desirable, by judicious identification of a regional cluster of users to share the joint inventory.

4. Reduction in the number of storage points generally increases transportation cost. Hence, it is important to evaluate the trade-off between simplified infrastructure and reduced investment in inventories against increases in transportation cost.

The example showcased in this analysis—distribution of spare engines for the F-16 in continental United States—amply supports open architecture as the right

design approach to reduce expenditures in the acquisition of valuable assets without compromising availability. The relevance here is far beyond the potential savings that the F-16 program could have enjoyed, but is a lesson for future government programs—whether they are weapons systems or other assets supplied by two or more qualified suppliers. Several examples come to mind, among them unmanned aerial vehicles, the space program and rail equipment.

Future studies about the impact of open architecture on complex systems should expand the analysis to incorporate benefits provided by simplified maintenance expenditures, as well as to investigate the additional cost and time required to coordinate the developmental efforts to ensure a common interface. On the distribution side, the regular adoption of transshipment (lateral shipment) or the use of multiple storage units to serve a given user should be studied as alternatives to improve inventory pooling, and thus to enhance the value of open architecture in future product development programs by the Department of Defense.

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Appendix

PRATT & WHITNEY (F100 ENGINE)										
Base	**ICAO**	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**2008 Forecast Mean**	**2008 Forecast Std Err**
ANG-Burlington VT	BTV	52	39	51	48	43	31	40	34.9	6.5
ANG-Duluth MN	DLH	49	52	56	38	30	27	33	23.0	7.1
ANG-Des Moines IA	DSM	40	37	32	28	12	25	13	8.9	5.7
ANG-Ellington TX	EFD	38	53	42	38	39	33	37	33.4	5.7
ANG-Fresno CA	FAT	57	35	41	45	36	34	55	41.4	10.3
ANG-Ft Smith AR	FSM	34	33	27	36	39	29	5	17.1	10.2
ANG-Ft Wayne IN	FWA	38	37	33	47	23	28	29	25.7	7.3
Hill AFB-Depot UT	HIF	56	71	64	54	67	67	67	67.7	6.5
Nellis AFB NV	LSV	88	57	92	90	97	66	60	69.9	17.7
Luke AFB AZ	LUF	365	355	344	327	338	273	250	248.1	19.1
Tinker AFB OK	TIK	0	0	0	0	0	0	0	0.0	0.0
ANG-Toledo OH	TOL	44	35	24	24	13	18	7	1.3	4.4
ANG-Tulsa OK	TUL	43	34	21	22	21	18	9	4.9	4.5
ANG-Tucson AZ	TUS	209	160	176	153	126	102	107	80.1	14.1
GENERAL ELECTRIC (F110 ENGINE)										
Base	**ICAO**	**'01**	**'02**	**'03**	**'04**	**'05**	**'06**	**'07**	**2008 Forecast Mean**	**2008 Forecast Std Err**
ANG-Albuquerque NM	ABQ	48	40	45	39	27	38	37	31.3	5.6
ANG-Eggharbor NJ	ACY	44	53	51	53	38	20	22	19.4	9.5
ANG-Andrews DC	ADW	33	39	26	21	34	29	26	25.0	6.0
ANG-Buckley CO	BKF	40	33	48	39	33	28	29	27.4	6.0
Cannon AFB NM	CVS	175	153	126	102	93	99	65	48.9	11.3
ANG-Sioux SD	FSD	42	60	49	42	43	45	42	41.0	6.6
ANG-Gt Falls MT	GTF	33	45	47	55	46	53	29	44.4	10.6
Hill AFB UT	HIF	245	201	225	236	202	230	220	217.0	17.8
AFR-Homestead FL	HST	40	31	41	32	34	26	33	28.4	4.7
ANG-Montgomery AL	MGM	39	30	50	46	26	45	34	37.3	9.8
ANG-Madison WI	MSN	45	33	33	33	28	25	36	26.4	5.6
ANG-Selfridge MI	MTC	65	45	47	51	37	43	33	30.1	6.6
AFR-Ft Worth TX	NFW	47	40	41	20	38	26	27	21.1	7.5
ANG-Richmond VA	RIC	36	42	37	36	20	25	6	8.7	7.0
ANG-Springfield OH	SGH	53	64	63	57	43	54	56	51.3	7.2
ANG-Kelly TX	SKF	61	49	46	56	50	49	46	45.1	5.0
ANG-Springfield IL	SPI	33	19	24	27	23	31	34	31.0	5.7
ANG-Syracuse NY	SYR	0	0	31	38	35	33	39	38.5	3.3
Tinker AFB OK	TIK	0	0	0	0	0	0	0	0.0	0.0

Sources: Historic data adapted from Henderson & Higer (2007) and http://www.f-16.net. Forecast by the author.

Table 8: Historic Demand of F100 and F110 Engines

PRATT & WHITNEY (F-100 ENGINE)						
		2008 Forecast		2008 Inventory		
Base	**ICAO**	**Mean**	**Std Err**	**Base Stock**	**Safety Stock**	**Distance from inventory (mi)**
Luke AFB AZ	LUF	248.1	19.1	16	4.9	0
ANG-Tucson AZ	TUS	80.1	14.1	at LUF		145
Nellis AFB NV	LSV	69.9	17.7	at LUF		278
ANG-Fresno CA	FAT	41.4	10.3	at LUF		579
Tinker AFB OK	TIK	0.0	0.0	3	1.8	0
ANG-Des Moines IA	DSM	8.9	5.7	at TIK		545
ANG-Ft Smith AR	FSM	17.1	10.2	at TIK		183
ANG-Ellington TX	EFD	33.4	5.7	at TIK		467
ANG-Tulsa OK	TUL	4.9	4.5	at TIK		119
ANG-Burlington VT	BTV	34.9	6.5	3	1.1	0
Hill AFB-Depot UT	HIF	67.7	6.5	3	1.1	0
ANG-Duluth MN	DLH	23.0	7.1	2	1.1	0
ANG-Ft Wayne IN	FWA	25.7	7.3	2	1.3	0
ANG-Toledo OH	TOL	1.3	4.4	at FWA		98

Note: Storage locations in **bold**.

Source: The author.

Table 9: Recommended Regional Storage of Pratt & Whitney Spare Engines

General Electric (F-110 Engine)						
Base	**ICAO**	**2008 Forecast**		**2008 Inventory**		**Distance from inventory (mi)**
		Mean	**Std Err**	**Base Stock**	**Safety Stock**	
Tinker AFB OK	TIK	0.0	0.0	3	1.2	0
ANG-Kelly TX	SKF	45.1	5.0	at TIK		485
AFR-Ft Worth TX	NFW	21.1	7.5	at TIK		211
Hill AFB UT	HIF	217.0	17.8	11	3.5	0
ANG-Gt Falls MT	GTF	44.4	10.6	at HIF		544
ANG-Andrews DC	ADW	25.0	6.0	5	2.3	0
ANG-Eggharbo NJ	ACY	19.4	9.5	at ADW		168
ANG-Syracuse NY	SYR	38.5	3.3	at ADW		386
ANG-Richmond VA	RIC	8.7	7.0	at ADW		122
ANG-Springfield OH	SGH	51.3	7.2	5	1.8	0
ANG-Selfridge MI	MTC	30.1	6.6	at SGH		253
ANG-Springfield IL	SPI	31.0	5.7	at SGH		347
AFR-Homestead FL	HST	28.4	4.7	2	0.8	0
ANG-Montgomery AL	MGM	37.3	9.8	3	1.5	0
Cannon AFB NM	CVS	48.9	11.3	5	2.0	0
ANG-Albuquerque NM	ABQ	31.3	5.6	at CVS		220
ANG-Buckley CO	BKF	27.4	6.0	at CVS		493
ANG-Sioux SD	FSD	41.0	6.6	3	1.4	0
ANG-Madison WI	MSN	26.4	5.6	at FSD		429

Note: Storage locations in **bold**.

Source: **The author.**

Table 10: Regional Storage of General Electric Spare Engines

		2008 Forecast		2008 Inventory		Distance from inventory (mi)
		Mean	Std Err	Base Stock	Safety Stock	
ANG-Albuquerque NM	ABQ	31.3		5	2.2	0
Cannon AFB NM	CVS	48.9		at ABQ		220
ANG-Buckley CO	BKF	27.4		at ABQ		453
ANG-Andrews DC	ADW	25.0		6	2.6	0
ANG-Richmond VA	RIC	8.7		at ADW		122
ANG-Syracuse NY	SYR	38.5		at ADW		386
ANG-Egg Harbor NJ	ACY	19.4		at ADW		168
ANG-Burlington VT	BTV	34.9		at ADW		523
Hill AFB UT	HIF	284.7		12	2.9	0
ANG-Gt Falls MT	GTF	44.4		at HIF		544
Luke AFB AZ	LUF	248.1		16	4.9	0
ANG-Fresno CA	FAT	41.4		at LUF		579
Nellis AFB NV	LSV	69.9		at LUF		278
ANG-Tucson AZ	TUS	80.1		at LUF		145
Tinker AFB OK	TIK	0.0		4	2.0	0
ANG-Ellington TX	EFD	33.4		at TIK		467
ANG-Ft Smith AR	FSM	17.1		at TIK		183
AFR-Ft Worth TX	NFW	21.1		at TIK		211
ANG-Kelly TX	SKF	45.1		at TIK		485
ANG-Tulsa OK	TUL	4.9		at TIK		119
ANG-Ft Wayne IN	FWA	25.7		7	2.4	0
ANG-Madison WI	MSN	26.4		at FWA		321
ANG-Selfridge MI	MTC	30.1		at FWA		194
ANG-Springfield OH	SGH	51.3		at FWA		141
ANG-Springfield IL	SPI	31.0		at FWA		328
ANG-Toledo OH	TOL	1.3		at FWA		98
ANG-Sioux SD	FSD	41.0		4	1.8	0
ANG-Duluth MN	DLH	23.0		at FSD		396
ANG-Des Moines IA	DSM	8.9		at FSD		292
AFR-Homestead FL	HST	28.4		2	0.8	0
ANG-Montgomery AL	MGM	37.3		3	1.5	0

Note: Storage locations in **bold**.

Source: **The author.**

Table 11: Regional Storage of Spare Engines with OA Benefit

2003 - 2008 Sponsored Research Topics

Acquisition Management

- Software Requirements for OA
- Managing Services Supply Chain
- Acquiring Combat Capability via Public-Private Partnerships (PPPs)
- Knowledge Value Added (KVA) + Real Options (RO) Applied to Shipyard Planning Processes
- Portfolio Optimization via KVA + RO
- MOSA Contracting Implications
- Strategy for Defense Acquisition Research
- Spiral Development
- BCA: Contractor vs. Organic Growth

Contract Management

- USAF IT Commodity Council
- Contractors in 21st Century Combat Zone
- Joint Contingency Contracting
- Navy Contract Writing Guide
- Commodity Sourcing Strategies
- Past Performance in Source Selection
- USMC Contingency Contracting
- Transforming DoD Contract Closeout
- Model for Optimizing Contingency Contracting Planning and Execution

Financial Management

- PPPs and Government Financing
- Energy Saving Contracts/DoD Mobile Assets
- Capital Budgeting for DoD
- Financing DoD Budget via PPPs
- ROI of Information Warfare Systems
- Acquisitions via leasing: MPS case
- Special Termination Liability in MDAPs

Human Resources

- Learning Management Systems
- Tuition Assistance
- Retention
- Indefinite Reenlistment
- Individual Augmentation

Logistics Management

- R-TOC Aegis Microwave Power Tubes
- Privatization-NOSL/NAWCI
- Army LOG MOD
- PBL (4)
- Contractors Supporting Military Operations
- RFID (4)
- Strategic Sourcing
- ASDS Product Support Analysis
- Analysis of LAV Depot Maintenance
- Diffusion/Variability on Vendor Performance Evaluation
- Optimizing CIWS Lifecycle Support (LCS)

Program Management

- Building Collaborative Capacity
- Knowledge, Responsibilities and Decision Rights in MDAPs
- KVA Applied to Aegis and SSDS
- Business Process Reengineering (BPR) for LCS Mission Module Acquisition
- Terminating Your Own Program
- Collaborative IT Tools Leveraging Competence

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